

# THE PAST AND FUTURE OF COULOMB DISSOCIATION IN HADRON- AND ASTROPHYSICS

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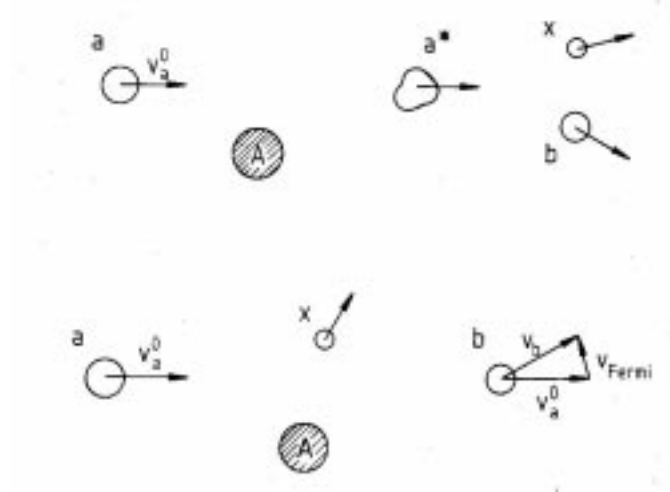
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**Abstract** Breakup reactions are generally quite complicated, they involve nuclear and electromagnetic forces including interference effects. Coulomb dissociation is an especially simple and important mechanism since the perturbation due to the electric field of the nucleus is exactly known. Therefore firm conclusions can be drawn from such measurements. Electromagnetic matrixelements, radiative capture cross-sections and astrophysical S-factors can be extracted from experiments. We describe the basic theory, give analytical results for higher order effects in the dissociation of neutron halo nuclei and briefly review the experimental results

obtained up to now. Some new applications of Coulomb dissociation for nuclear astrophysics and nuclear structure physics are discussed.

## 1. INTRODUCTION

One may regard the work of Oppenheimer and Phillips in 1935 [1, 2] as a starting point of the present subject. They tried to explain the preponderance of (d,p)-reactions over (d,n)-reactions by a virtual breakup of the deuteron in the Coulomb field of the nucleus before the actual nuclear interaction takes place. Because of the Coulomb repulsion of the proton this would explain the dominance of (d,p)-reactions. In this context, Oppenheimer [1] also treated the real breakup of the deuteron in the Coulomb field of a nucleus. In the meantime, the subject has developed considerably. In addition to the deuteron, many different kinds of projectiles (ranging from light to heavy ions, including radioactive nuclei) have been used at incident energies ranging from below the Coulomb barrier to medium and up to relativistic energies.



*Figure 1* Two basic reaction mechanisms for breakup are shown schematically. In the upper figure (sequential breakup), the projectile  $a$  is excited to a continuum (resonant) state  $a^*$  which decays subsequently into the fragments  $b$  and  $x$ . In the lower part (spectator breakup) substructure  $x$  interacts (in all kinds of ways) with the target nucleus  $A$ , whereas  $b = (a - x)$  misses the target nucleus (“spectator”). It keeps approximately the velocity which it had before the collision. [Fig. 1 of Ref. [3].]

In Fig. 1 we show two different kinds of reaction mechanisms. Since rigorous methods of reaction theory (like the Faddeev approach) cannot

be applied in practice to such complicated nuclear reactions, we have to use different theoretical methods to treat the different cases as well as possible. In the spectator breakup mechanism the breakup occurs due to the interaction of one of the constituents with the target nucleus, while the spectator moves on essentially undisturbed. Another mechanism is the sequential breakup, where the projectile is excited to a continuum state which decays subsequently. Both mechanisms have been dealt with extensively in the past [3], see also Ref. [4], which provides a brief outline of the development over the last few decades. For low and medium energies (i.e., for energies not high enough for the Glauber theory to be applicable) it should be noted that the post-form DWBA is especially suited to treat the spectator process. For the sequential breakup mechanism the decomposition of the Hamiltonian in the initial and final channels is the same.

We start with a general discussion of Coulomb dissociation. Due to the time-dependent electromagnetic field the projectile is excited to a bound or continuum state, which can subsequently decay. We briefly mention the very large effects of electromagnetic excitation in relativistic heavy ion collisions. After a short review of results obtained for nuclear structure as well as nuclear astrophysics, we discuss new possibilities, like the experimental study of two-particle capture. We close with conclusions and an outlook.

## 2. ELECTROMAGNETIC AND NUCLEAR DISSOCIATION

Coulomb excitation is a very useful tool to determine nuclear electromagnetic matrixelements. The nuclei are assumed to interact with each other only electromagnetically. This can be achieved by either using bombarding energies below the Coulomb barrier or by choosing very forward scattering angles and high energy collisions. With increasing beam energy states at higher energies can be excited; this can lead, in addition to Coulomb excitation, also to Coulomb dissociation, for a review see, e.g., Ref. [5]. Such investigations are also well suited for secondary (radioactive) beams. The electromagnetic interaction, which causes the dissociation, is well known and therefore there can be a clean interpretation of the experimental data. This is of interest for nuclear structure and nuclear astrophysics [6, 7]. Multiple electromagnetic excitation can also be important. We especially mention two aspects: It is a way to excite new nuclear states, like the double phonon giant dipole resonance [7]; but it can also be a correction to the one-photon excitation [8, 9, 10].

In the equivalent photon approximation the cross section for an electromagnetic process is written as

$$\sigma = \int \frac{d\omega}{\omega} n(\omega) \sigma_\gamma(\omega) \quad (1.1)$$

where  $\sigma_\gamma(\omega)$  denotes the appropriate cross section for the photo-induced process and  $n(\omega)$  is the equivalent photon number. For sufficiently high beam energies it is well approximated by

$$n(\omega) = \frac{2}{\pi} Z^2 \alpha \ln \frac{\gamma v}{\omega R} \quad (1.2)$$

where  $R$  denotes some cut-off radius. More refined expressions, which take into account the dependence on multipolarity, beam velocity or Coulomb-deflection, are available in the literature [5, 9, 11]. The theory of electromagnetic excitation is well developed for nonrelativistic, as well as relativistic projectile velocities. In the latter case an analytical result for all multiplicities was obtained in Ref. [11]. The projectile motion was treated classically in a straight-line approximation. On the other hand, in the Glauber theory, the projectile motion can be treated quantum mechanically [5, 10]. This gives rise to characteristic diffraction effects. The main effect is due to the strong absorption at impact parameters less than the sum of the two nuclear radii.

If the above conditions are not met, nuclear excitation (or diffractive dissociation) also has to be taken into account. This is a broad subject and has been studied in great detail using Glauber theory, see, e.g., [5] for further references. Especially for light nuclei, Coulomb excitation tends to be less important in general than nuclear excitation. For heavy nuclei the situation reverses. The nuclear breakup of halo nuclei was more recently studied, e.g., in [12]. The nuclear interaction of course is less precisely known than the Coulomb interaction. In Ref. [12] the nuclear breakup was studied using the eikonal approximation as well as the Glauber multiple particle scattering theory. No Coulomb interaction was included in this approach, as the main focus was on the breakup on light targets. In Ref. [13] on the other hand, the combined effect of both nuclear and Coulomb excitation is studied. The nuclear contribution to the excitation is generally found to be small and has an angular dependence different from the electromagnetic one. This can be used to separate such effects from the electromagnetic excitation. We also mention the recent systematic study of  $^8\text{B}$  breakup cross section in [14].

### 3. ELECTROMAGNETIC EXCITATION IN RELATIVISTIC HEAVY ION COLLISIONS

Electromagnetic excitation is also used at relativistic heavy ion accelerators to obtain nuclear structure information. Recent examples are the nuclear fission studies of radioactive nuclei [15] and photofission of  $^{208}\text{Pb}$  [16]. Cross-sections for the excitation of the giant dipole resonance (“Weizsäcker-Williams process”) at the forthcoming relativistic heavy ion colliders RHIC and LHC(Pb-Pb) at CERN are huge [17, 18], of the order of 100 b for heavy systems (Au-Au or Pb-Pb). In colliders, the effect is considered to be mainly a nuisance, the excited particles are lost from the beam. On the other hand, the effect will also be useful as a luminosity monitor by detecting the neutrons in the forward direction. Specifically one will measure the neutrons which will be produced after the decay of the giant dipole resonance which is excited in each of the ions (simultaneous excitation). Since this process has a steeper impact parameter dependence than the single excitation cross-section, there is more sensitivity to the cut-off radius and to nuclear effects. For details and further Refs., see [18].

### 4. HIGHER ORDER EFFECTS AND POSTACCELERATION

Higher order effects can be taken into account in a coupled channels approach, or by using higher order perturbation theory. The latter involves a sum over all intermediate states  $n$  considered to be important. Another approach is to integrate the time-dependent Schrödinger equation directly for a given model Hamiltonian [19, 20, 21, 22]. If the collision is sudden, one can neglect the time ordering in the usual perturbation approach. The interaction can be summed to infinite order. Intermediate states  $n$  do not appear explicitly.

Higher order effects were recently studied in [23], where further references also to related work can be found. Since full Coulomb wave functions in the initial and final channels are used there, the effects of higher order in  $\eta_{\text{coul}} = \frac{ZZ_c e^2}{\hbar v}$  are taken into account to all orders. Expanding the T-matrixelement in this parameter  $\eta_{\text{coul}}$  one obtains the Born approximation for the dissociation of  $a \rightarrow c + n$

$$T \propto \frac{\eta_{\text{coul}}}{(\vec{q}_n + \vec{q}_c - \vec{q}_a)^2} \left( \frac{1}{q_a^2 - (\vec{q}_n + \vec{q}_c)^2} + \frac{1}{q_c^2 - (\vec{q}_n - \vec{q}_a)^2} \right). \quad (1.3)$$

This expression is somehow related to the Bethe-Heitler formula for bremsstrahlung. The Bethe-Heitler formula has two terms which correspond to a Coulomb interaction of the electron and the target followed

by the photon emission and another one, where the photon is emitted first and then the electron scatters from the nucleus. In the case of Coulomb dissociation we have a Coulomb scattering of the incoming particle followed by breakup  $a=(c+n) \rightarrow c+n$  and another term, where the projectile  $a$  breaks up into  $c+n$ , and subsequently,  $c$  is scattered on the target. In the case of bremsstrahlung it is well known [24] that even for  $\eta_{coul} \gg 1$  one obtains the Born approximation result as long as the scattering is into a narrow cone in the forward direction. This leads one to suspect that higher order effects are not very large in the case of high energy Coulomb dissociation, when the fragments are emitted into the forward direction.

We investigate higher order effects in the model of [8, 9, 10]. In a zero range model for the neutron-core interaction, analytical results were obtained for 1<sup>st</sup> and 2<sup>nd</sup> order electromagnetic excitation for small values of the adiabaticity parameter  $\xi$ . We are especially interested in collisions with small impact parameters. For these higher order effects tend to be larger than for the very distant ones. In this case, the adiabaticity parameter  $\xi$  is small. For  $\xi = 0$  (sudden approximation) we have a closed form solution, where higher order effects are taken into account to all orders. In eq. 37 of [8] the angle integrated breakup probability is given. We expand this expression in the strength parameter  $\eta_{\text{eff}} = \frac{2ZZ_c e^2 m_n}{\hbar v(m_n + m_c)}$ . We define  $x = \frac{q}{\eta}$  where the parameter  $\eta$  is related to the binding energy  $E_0$  by  $E_0 = \frac{\hbar^2 \eta^2}{2m}$  and the wave number  $q$  is related to the energy  $E_{\text{rel}}$  of the continuum final state by  $E_{\text{rel}} = \frac{\hbar^2 q^2}{2\mu}$ . In leading order (LO) we obtain

$$\frac{dP_{LO}}{dq} = C \frac{x^4}{(1+x^2)^4} \quad (1.4)$$

where  $C = \frac{128\pi^2 \eta_{\text{eff}}^2}{3\eta^3 b^2}$ . The next to leading order (NLO) expression is proportional to  $\eta_{\text{eff}}^4$  and contains a piece from the 2nd order E1 amplitude and a piece from the interference of 1st and 3rd order. We find

$$\frac{dP_{NLO}}{dq} = C \left( \frac{\eta_{\text{eff}}}{b\eta} \right)^2 \frac{x^2(5 - 55x^2 + 28x^4)}{15(1+x^2)^6}. \quad (1.5)$$

The integration over  $x$  and the impact parameter  $b$  can also be performed analytically in good approximation. For details see [25]. We can easily insert the corresponding values for the Coulomb dissociation experiments on  $^{11}\text{Be}$  and  $^{19}\text{C}$  [26, 27] in the present formulae. We find that the ratio of the NLO contribution to the LO contribution in the case of Coulomb dissociation on  $^{19}\text{C}$  [27] is given by  $-2\%$ . This is to be compared to the results of [23] where a value of about  $-35\%$  was found.

## 5. DISCUSSION OF SOME EXPERIMENTAL RESULTS FOR NUCLEAR STRUCTURE AND ASTROPHYSICS

Coulomb dissociation of exotic nuclei is a valuable tool to determine electromagnetic matrix-elements between the ground state and the nuclear continuum. The excitation energy spectrum of the  $^{10}\text{Be}+n$  system in the Coulomb dissociation of the one-neutron halo nucleus  $^{11}\text{Be}$  on a Pb target at 72-A MeV was measured [26]. Low lying E1-strength was found. The Coulomb dissociation of the extremely neutron-rich nucleus  $^{19}\text{C}$  was recently studied in a similar way [27]. The neutron separation energy of  $^{19}\text{C}$  could also be determined to be  $530 \pm 130$  keV. Quite similarly, the Coulomb dissociation of the 2n-halo nucleus  $^{11}\text{Li}$  was studied in various laboratories [28, 29, 30]. In an experiment at MSU [31], the correlations of the outgoing neutrons were studied. Within the limits of experimental accuracy, no correlations were found.

In nuclear astrophysics, radiative capture reactions of the type  $b+c \rightarrow a + \gamma$  play a very important role. They can also be studied in the time-reversed reaction  $\gamma+a \rightarrow b+c$ , at least in those cases where the nucleus  $a$  is in the ground state. As a photon beam, we use the equivalent photon spectrum which is provided in the fast peripheral collision. Reviews, both from an experimental as well as theoretical point of view have been given [6], so we want to concentrate here on a few points.

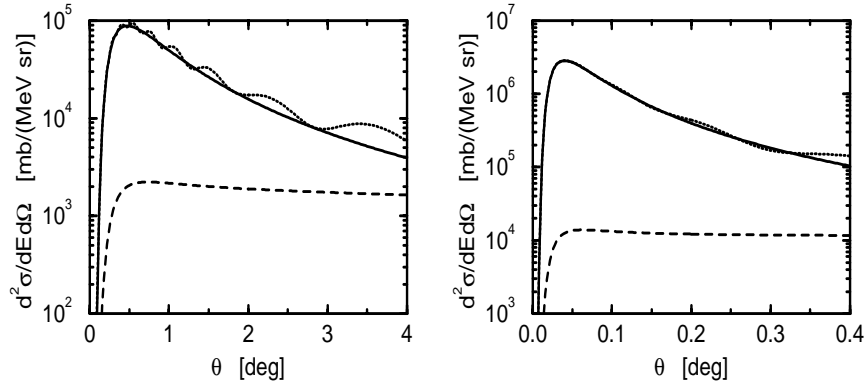


Figure 2 Coulomb dissociation cross section of  $^8\text{B}$  scattered on  $^{208}\text{Pb}$  as a function of the scattering angle for projectile energies of 46.5 A-MeV (left) and 250 A-MeV (right) and a  $^7\text{Be}$ -p relative energy of 0.3 MeV. First order results E1 (solid line), E2 (dashed line) and E1+E2 excitation including nuclear diffraction (dotted line). [From Figs. 4 and 5 of Ref. [10].]

The  ${}^6\text{Li}$  Coulomb dissociation into  $\alpha+d$  has been a test case of the method, see Ref. [6]. This is of importance since the  $d(\alpha,\gamma){}^6\text{Li}$  radiative capture is the only process by which  ${}^6\text{Li}$  is produced in standard primordial nucleosynthesis models. There has been new interest in  ${}^6\text{Li}$  as a cosmological probe in recent years, mainly because the sensitivity for searches for  ${}^6\text{Li}$  has been increasing. It has been found in metal-poor halo stars at a level exceeding even optimistic estimates of how much  ${}^6\text{Li}$  could have been made in standard big bang nucleosynthesis. For more discussion on this see [32].

The  ${}^7\text{Be}(p,\gamma){}^8\text{B}$  radiative capture reaction is relevant for the solar neutrino problem. It determines the production of  ${}^8\text{B}$  which leads to the emission of high energy neutrinos. There are direct reaction measurements, for a recent one see Refs. [33]. Coulomb dissociation of  ${}^8\text{B}$  has been studied at RIKEN [34], MSU [35] and GSI [36]. Theoretical calculations are shown in Fig. 2. It is seen that E1 excitation is large and peaked at very forward angles. E2 excitation is also present, with a characteristically different angular distribution. Nuclear diffraction effects are small. Altogether it is quite remarkable that completely different experimental methods with possibly different systematic errors lead to results that are quite consistent.

## 6. POSSIBLE NEW APPLICATIONS OF COULOMB DISSOCIATION FOR NUCLEAR ASTROPHYSICS

Nucleosynthesis beyond the iron peak proceeds mainly by the r- and s-processes (rapid and slow neutron capture) [37, 38]. To establish the quantitative details of these processes, accurate energy-averaged neutron-capture cross sections are needed. Such data provide information on the mechanism of the neutron-capture process and time scales, as well as temperatures involved in the process. The data should also shed light on neutron sources, required neutron fluxes and possible sites of the processes (see Ref. [37]). The dependence of direct neutron capture on nuclear structure models was investigated in Ref. [39]. The investigated models yield capture cross-sections sometimes differing by orders of magnitude. This may also lead to differences in the predicted astrophysical r-process paths. Because of low level densities, the compound nucleus model will not be applicable.

With the new radioactive beam facilities (either fragment separator or ISOL-type facilities) some of the nuclei far off the valley of stability, which are relevant for the r-process, can be produced. In order to assess the r-process path, it is important to know the nuclear properties like



$\beta$ -decay half-lives and neutron binding energies. Sometimes, the waiting point approximation [37, 38] is introduced, which assumes an  $(n, \gamma)$ - and  $(\gamma, n)$ -equilibrium in an isotopic chain. It is generally believed that the waiting point approximation should be replaced by dynamic r-process flow calculations, taking into account  $(n, \gamma)$ ,  $(\gamma, n)$  and  $\beta$ -decay rates as well as time-varying temperature and neutron density. In slow freeze-out scenarios, the knowledge of  $(n, \gamma)$  cross sections is important.

In such a situation, the Coulomb dissociation can be a very useful tool to obtain information on  $(n, \gamma)$ -reaction cross sections on unstable nuclei, where direct measurements cannot be done. Of course, one cannot and need not study the capture cross section on all the nuclei involved; there will be some key reactions of nuclei close to magic numbers. It was proposed [40] to use the Coulomb dissociation method to obtain information about  $(n, \gamma)$  reaction cross sections, using nuclei like  $^{124}\text{Mo}$ ,  $^{126}\text{Ru}$ ,  $^{128}\text{Pd}$  and  $^{130}\text{Cd}$  as projectiles. The optimum choice of beam energy will depend on the actual neutron binding energy. Since the flux of equivalent photons has essentially an  $\frac{1}{\omega}$  dependence, low neutron thresholds are favourable for the Coulomb dissociation method. Note that only information about the  $(n, \gamma)$  capture reaction to the ground state is possible with the Coulomb dissociation method. The situation is reminiscent of the loosely bound neutron-rich light nuclei, like  $^{11}\text{Be}$ ,  $^{11}\text{Li}$  and  $^{19}\text{C}$ .

In Ref. [8] the  $1^{\text{st}}$  and  $2^{\text{nd}}$  order Coulomb excitation amplitudes are given analytically in a zero range model for the neutron-core interaction (see section 4). We propose to use the handy formalism of Ref. [8] to assess, how far one can go down in beam energy and still obtain meaningful results with the Coulomb dissociation method, i.e., where the  $1^{\text{st}}$  order amplitude can still be extracted experimentally without being too much disturbed by corrections due to higher orders. For future radioactive beam facilities, like ISOL od SPIRAL, the maximum beam energy is an important issue. For Coulomb dissociation with two charged particles in the final state, like in the  $^8\text{B} \rightarrow ^7\text{Be} + \text{p}$  experiment with a 26 MeV  $^8\text{B}$  beam [41] such simple formulae seem to be unavailable and one should resort to the more involved approaches mentioned in section 4.

A new field of application of the Coulomb dissociation method can be two nucleon capture reactions. Evidently, they cannot be studied in a direct way in the laboratory. Sometimes this is not necessary, when the relevant information about resonances involved can be obtained by other means (transfer reactions, etc.), like in the triple  $\alpha$ -process.

Two-neutron capture reactions in supernovae neutrino bubbles are studied in Ref. [42]. In the case of a high neutron abundance, a sequence

of two-neutron capture reactions,  ${}^4\text{He}(2n,\gamma){}^6\text{He}(2n,\gamma){}^8\text{He}$  can bridge the  $A = 5$  and 8 gaps. The  ${}^6\text{He}$  and  ${}^8\text{He}$  nuclei may be formed preferentially by two-step resonant processes through their broad  $2^+$  first excited states [42]. Dedicated Coulomb dissociation experiments can be useful, see [43]. Another key reaction can be the  ${}^4\text{He}(\alpha n,\gamma)$  reaction [42]. The  ${}^9\text{Be}(\gamma,n)$  reaction has been studied directly (see Ref. [44]) and the low energy  $s_{\frac{1}{2}}$  resonance is clearly established.

In the rp-process, two-proton capture reactions can bridge the waiting points [45, 46, 47]. From the  ${}^{15}\text{O}(2p,\gamma){}^{17}\text{Ne}$ ,  ${}^{18}\text{Ne}(2p,\gamma){}^{20}\text{Mg}$  and  ${}^{38}\text{Ca}(2p,\gamma){}^{40}\text{Ti}$  reactions considered in Ref. [46], the latter can act as an efficient reaction link at conditions typical for X-ray bursts on neutron stars. A  ${}^{40}\text{Ti} \rightarrow p + p + {}^{38}\text{Ca}$  Coulomb dissociation experiment should be feasible. The decay with two protons is expected to be sequential rather than correlated ( ${}^2\text{He}$ -emission). The relevant resonances are listed in Table XII of Ref. [46]. In Ref. [47] it is found that in X-ray bursts 2p-capture reactions accelerate the reaction flow into the  $Z \geq 36$  region considerably. In Table 1 of Ref. [47] nuclei, on which 2p-capture reactions may occur, are listed; the final nuclei are  ${}^{68}\text{Se}$ ,  ${}^{72}\text{Kr}$ ,  ${}^{76}\text{Sr}$ ,  ${}^{80}\text{Zr}$ ,  ${}^{84}\text{Mo}$ ,  ${}^{88}\text{Ru}$ ,  ${}^{92}\text{Pd}$  and  ${}^{96}\text{Cd}$  (see also Fig. 8 of Ref. [45]). It is proposed to study the Coulomb dissociation of these nuclei in order to obtain more direct insight into the 2p-capture process.

## 7. CONCLUSIONS

Peripheral collisions of medium and high energy nuclei (stable or radioactive) passing each other at distances beyond nuclear contact and thus dominated by electromagnetic interactions are important tools of nuclear physics research. The intense source of quasi-real (or equivalent) photons has opened a wide horizon of related problems and new experimental possibilities especially for the present and forthcoming radioactive beam facilities to investigate efficiently photo-interactions with nuclei (single- and multiphoton excitations and electromagnetic dissociation).

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